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955 L'Enfant Plaza North, S.W.
Washington, D. C. 20024

date: August 5, 1971

to: Distribution

from: A. W. Zachar

B71 08007

subject: Skylab Saturn Workshop Diffusely Reflected Solar Light at the CSM During Rendezvous - Case 620

ABSTRACT

Skylab CSM/Saturn Workshop rendezvous procedures using CSM optics require that the CSM visually track the Saturn Workshop (SWS) during certain phases of the rendezvous. Visibility of the SWS is a function of its size, distance from the viewer (CSM) and its brightness relative to the background brightness. This memorandum is concerned with the brightness of the SWS when viewed from the CSM during rendezvous.

Luminous flux data at the CSM due to Lambert diffuse reflection of direct solar and earth reflected solar light from the SWS have been numerically determined in accordance with governing equations using existing shadow, heat flux and navigation computer programs. The flux and shadow programs required that the SWS be modeled as a group of properly oriented flat plates defined by their normals.

Output from the aforementioned programs was used by a fourth program titled "SWS Luminous Flux at CSM During Rendezvous" to generate the desired luminous flux data. A sample case, corresponding to a November 9, 1972 SL-1 launch date, was run for the SWS in a local vertical attitude and assuming a cloudless earth. These data are presented in Figure 7.

(NASA-CR-121319) SKYLAB SATURN WORKSHOP DIFFUSELY REFLECTED SOLAR LIGHT AT THE CSM DURING RENDEZVOUS (Bellcomm, Inc.) 18 p

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MEMORANDUM FOR FILE

Introduction

Skylab CSM/Saturn Workshop rendezvous procedures using CSM optics require that the CSM visually track the Saturn Workshop (SWS) during certain phases of the rendezvous. Visibility of the SWS is a function of its size, distance from the viewer (CSM) and its brightness relative to the background brightness. This memorandum is concerned with the brightness of the SWS when viewed from the CSM during rendezvous.

Luminous flux data at the CSM due to Lambert diffuse reflection of direct solar and earth reflected solar light from the SWS are presented for the earth oriented (E.O.) SWS attitude for an M=5, SL-4 rendezvous based a November 9, 1972 SL-1 launch date, (see Figure 1). The data, corresponding to a sun angle (β) of -13.2° were computed using a computer program, titled "SWS Luminous Flux at CSM During Rendezvous", written for this purpose. Input to this program includes the output from three other computer programs titled "Shadow", "Thermal Flux Incident Heat" [1]* and "Navigation and Guidance Simulator, (NAGS)", [2].

Skylab CSM/SWS Orientation During Rendezvous

The SWS completes approximately five earth orbits during the period from CSM launch to rendezvous. During the first two and one half orbits the SWS maintains a solar inertial (S.I.) attitude, then converts to an earth oriented attitude for two more orbits and finally reverts back to the S.I. attitude for about one half orbit just prior to rendezvous. During rendezvous,

* Numbers in square brackets are reference numbers.

the CSM is generally below the SWS and very nearly in the SWS orbital plane. It is for this reason that earth albedo effects are most important with respect to SWS visibility. That is, except for the periods from SWS sunrise to 90° before orbital noon and 90° after orbital noon to SWS sunset, most of the SWS reflected light reaching the CSM is due to earth reflected solar light.

The position of the CSM relative to the SWS during rendezvous is provided by the NAGS computer program of reference 2.

SWS Visibility Model

The SWS visibility model has been defined in terms of the painted white surfaces as shown in Figures 2, 3, & 4. All white surfaces were assumed to have a reflectivity (ρ_C) of .75 and to reflect in a Lambert diffuse manner.

Analysis

Lambert diffuse reflection from a differential area is given by [3]

$$dI_{\alpha_v} = \frac{\rho E_s}{\pi} \cos\alpha_s \cos\alpha_v \, dA \quad \text{(lumens/steradian)} \tag{1}$$

where

- dI_{α_v} is the differential luminous intensity in the direction of the viewer due to reflected, visible solar flux
- ρ is the reflectivity of the surface
- E_s is the solar visible luminous flux per unit of incident-beam cross section
- α_s is the angle between the normal and solar vectors
- α_v is the angle between the normal and viewing vectors

as shown in Figure 5. This equation assumes parallel light rays.

The total luminous intensity in the direction of the viewer is obtained by integrating equation (1) over the surface in question. Thus

$$I_{\alpha_v} = \frac{\rho E_s}{\pi} \iint_A \cos\alpha_s \cos\alpha_v \, dA \quad \text{(lumens/steradian)} \tag{2}$$

Diffuse reflection from the SWS in the direction of the CSM due to Earth reflected solar light may be formulated using equation (1) twice. That is,

$$dI_{\alpha_{v_c}} = \frac{\rho_c \rho_e E_s}{\pi^2} \frac{\cos\alpha_{s_c} \cos\alpha_{v_c} \cos\alpha_{s_e} \cos\alpha_{v_e} \, dA_e \, dA_c}{(|\vec{v}_e|)^2} \quad \text{(lumens/steradian)} \tag{3}$$

where

$dI_{\alpha_{v_c}}$ is the differential luminous intensity in the direction of the CSM from the SWS due to earth reflected solar light

ρ_c is the spacecraft reflectivity

ρ_e is the earth reflectivity

E_s is the visible portion of the solar spectrum.

The other parameters define the light source and viewing vectors as shown in Figure 6.

Integration of equation (3) is simplified when the spacecraft reflecting surface is a flat plate, for then

$$I_{\alpha_{v_c}} = \frac{\rho_c \rho_e E_s \cos\alpha_{v_c} A_c}{\pi^2} \iint_{A_e} \frac{\cos\alpha_{s_c} \cos\alpha_{s_e} \cos\alpha_{v_e}}{(|\vec{v}_e|)^2} \, dA_e \tag{4}$$

The integration of equation 4 over the earth's surface has been accomplished numerically using the "Thermal Flux Incident Heat" computer program of reference 1. This program also provides the direct solar component of incident flux on a flat plate. Thus, the total flux incident on a spacecraft flat plate element may be written

$$I_{\alpha_{v_c}} = \left(\frac{\rho_c E_s \cos\alpha_{v_c} A_c}{\pi} \right) \left(Q_{i_{c_d}} + \rho_e Q_{i_{c_r}} \right) \tag{5}$$

where $Q_{i_{c_d}}$ and $Q_{i_{c_r}}$ are the incident heat flux components due to direct and earth reflected solar light respectively.

Since this program computes the direct and earth reflected solar flux incident on <u>any</u> arbitrarily oriented flat plate, all spacecraft cylindrical members have been represented by eight appropriately oriented flat plates. This has been done even though the direct solar flux incident on a cylinder could have been obtained analytically by integrating equation 1. The integration of equation 3 for the earth reflected case, however, is very difficult. It is noted, that equation 4 has previously been evaluated analytically for several special cases; see reference 4. Use of these results for the problem under consideration is, however, not convenient.

<u>Visibility Computer Program - Input</u>

The computer program, "SWS Luminous Flux at CSM During Rendezvous", accepts the following input:

1. The incident solar and earth reflected light flux on the various white components of the SWS.

2. Pointing angles and range from the SWS to the CSM during rendezvous.

3. The areas of the segments into which the white components of the SWS have been divided; 53 in all.

4. The three components of the unit normal to each of these segments.

5. Elapsed time from CSM orbit insertion.

6. Cluster shadowing and blockage relative to CSM Line of Sight (LOS) information for each segment.

7. The reflectivities of the spacecraft white portions (.75) and of a cloudless earth (.39).

8. The visible portion of the solar constant, (12,700 lumens/ft.^{2})

9. A spacecraft reflectivity degradation value.

Computation

The computations were made in accordance with equation (5). The first calculation determined which of the 53 SWS white segements are seen by the CSM. This was done by forming the dot product between the normal to the surface and the CSM LOS vector. Positive values of the dot product indicate that the segment can be seen. The dot product of these two vectors is also equal to the $\cos\alpha_{v_c}$ of equation (5).

Shadowing & Blockage

The incident flux data (Q_{i_c}) resulting from direct and earth reflected solar light were modified by shadow and blockage data obtained from the shadow program. This program determines the portion of each element that is shadowed by all other elements. Since only parallel light rays are considered, the earth reflected solar light incident on the SWS has not been modified by shadow data.

Blockage refers to the reduction in SWS reflected light due to the presence of cluster components in the CSM line-of-sight. It is apparent that this information can also be obtained using the shadow program; that is, simply replace the sun by the viewer. This has been done and the resulting data were used directly to modify the earth reflected incident light.

Note that it is possible for the same white surface to be both shadowed and blocked. Knowing that a particular element is, say, 50% shadowed and 50% blocked is not sufficient since the same portion of the element may be both shadowed and blocked. To assume that the element is either 50% shadowed/blocked or 100% shadowed/blocked would be incorrect.

It is apparent that if the sun vector and the CSM LOS vector are coincident, the same portion of a single element is both shadowed and blocked. Likewise, if these vectors exactly oppose one another, the portion of a single element that is shadowed cannot possibly be blocked. Using this boundary information, it was assumed that a reasonable representation of combined shadow and blockage behavior could be obtained by multiplying the smaller number (percent of shadowing or blockage) by sin $\eta/2$ and adding it to the larger number; where η is the angle between the sun vector and the CSM LOS vector. A final check was made to insure that the resulting sum was ≤ 1.

A review of the output showed that for the greater majority (approximately 85%) of the data points, the shadow or blockage factor was either zero or one and multiplication by sin $\eta/2$ was not required. Of the remaining 15% approximately half had one factor much smaller than the other and multiplication by sin $\eta/2$ affected the final result very little. Thus, for this case, if the multiplication term (sin $\eta/2$) was in error by as much as 50%, the final result would be in error by approximately 2%; that is, combined shadow and blockage = shadow + blockage $\cdot$ sin $\eta/2$ (or = shadow $\cdot$ sin $\eta/2$ + blockage) had meaning for only 7.5% of the data points.

It is concluded that multiplying the smaller factor by sin $\eta/2$ provides a good approximation to combined shadow and blockage (SHDBLK) behavior. The direct solar incident light was then modified by the SHDBLK data.

Luminous Intensity and Flux

The total normalized luminous intensity in the direction of the CSM was computed by multiplying the Q_{i_c} by $\cos\alpha_{v_c}$, A_c and dividing by π, as in equation 5. (The Q_{i_c} are for $E_s=\rho_e=1$).* That is,

$$\bar{I}_{\alpha_{v_c}} = \left(\frac{\cos\alpha_{v_c} A_c}{\pi}\right)\left(Q_{i_{c_d}} + Q_{i_{c_r}}\right) \tag{6}$$

*Setting E_s and ρ_e equal to one provided normalized luminous intensity data from which luminous intensity data for any values of E_s and ρ_e can be easily obtained.

The normalized luminous flux $(\bar{E}_{\alpha_{v_c}})$ at the CSM was determined using

$$\bar{E}_{\alpha_{v_c}} = \frac{\bar{I}_{\alpha_{v_c}}}{(|\vec{V}_c|)^2} \tag{7}$$

Finally, the actual luminous flux $(E_{\alpha_{v_c}})$ at the CSM was found as

$$E_{\alpha_{v_c}} = (\rho_c E_s) \left(\bar{E}_{\alpha_{v_{c_d}}} + \rho_e \bar{E}_{\alpha_{v_{c_r}}}\right) \text{(lumens/meter}^2\text{)} \tag{8}$$

where $\bar{E}_{\alpha_{v_c}} = \bar{E}_{\alpha_{v_{c_d}}} + \bar{E}_{\alpha_{v_{c_r}}}$ (9)

Numerical Results

Figure 7 presents the SWS reflected luminous flux (lumens/meter^2) at the CSM during rendezvous for the SWS in a local vertical attitude. Since SWS attitude during rendezvous is a combination of both local vertical and solar inertial, these data would also have to be obtained for the solar inertial case. The portion of the rendezvous during which the SWS is expected to be in the local vertical attitude is indicated by the dashed lines in this figure. Also shown are the portions of the rendezvous during which the earth and the earth plus a 400,000 ft. altitude occlude the SWS when viewed from the CSM. The rapid rise and drop in luminous flux occuring immediately after sunrise and reaching a minimum at 90° before orbital noon is due to the direct solar light on the solar panels. This effect is masked between 90° after orbital noon and sunset by the large amount of light being reflected from the Airlock Module (AM) and Mulitple Docking Adaptor (MDA), (see Figure 2).

The data were obtained for the following rendezvous trajectory conditions:

1. Nominal phase, M=5 rendezvous
2. Launch at 16:57:23 UT on May 1, 1973
3. Sun angle $\beta = -13.2°$

Elapsed time in seconds from launch is given at the top of Figure 7. These results are to be used in conjunction with background brightness and visibility criteria data.

Acknowledgements

The author wishes to acknowledge the programming assistance of Miss Dixie P. Nash who assembled various components of the shadow program to produce the SHDBLK data and ultimately the luminous flux data; also, Mr. Robert C. Purkey for providing the CSM LOS data.

1022-AWZ-tla

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Attachments

REFERENCES

1. Powers, J. W., "Spacecraft Shadowing and Thermal Flux Computer Programs with Sample Problems," Bellcomm Memorandum for File, July 8, 1968.

2. Guffee, C. O., "NAGS-A General Purpose Navigation and Guidance Simulation Program for Study of Space Missions," Bellcomm Memorandum for File, in preparation.

3. Brand, K. W., and F. A. Spagnolo, "Lambert Diffuse Reflection from General Quadric Surfaces," Journal of the Optical Soc. of Am., Vol. 57, No. 4, Apr. 1967.

4. Elrod, B. D. "Analytical Evaluation of View Factors for Calculating Incident Thermal Radiation on Spacecraft Surfaces," Bellcomm Technical Memorandum, to be published.

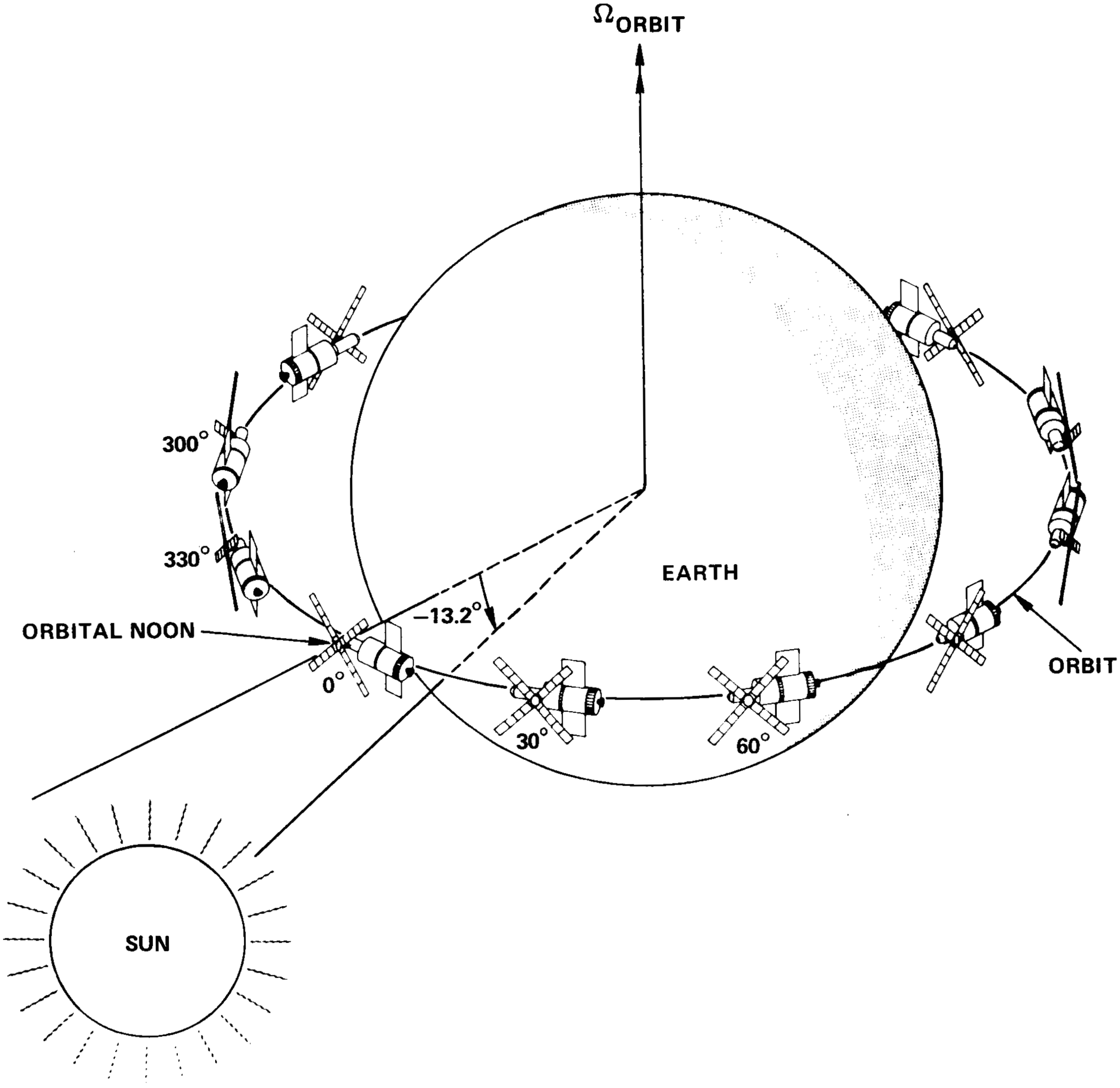
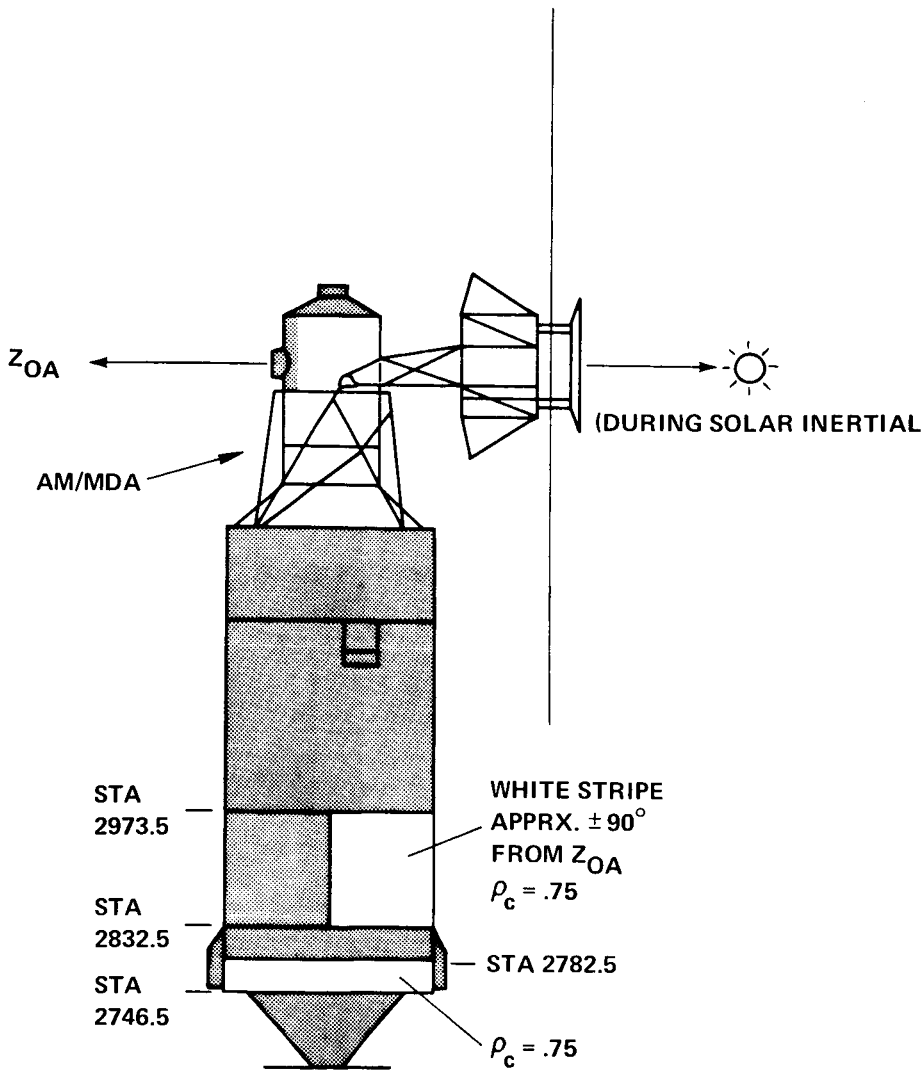


FIGURE 1 - SWS IN LOCAL VERTICAL ATTITUDE, SUN ANGLE (β) EQUALS −13.2°

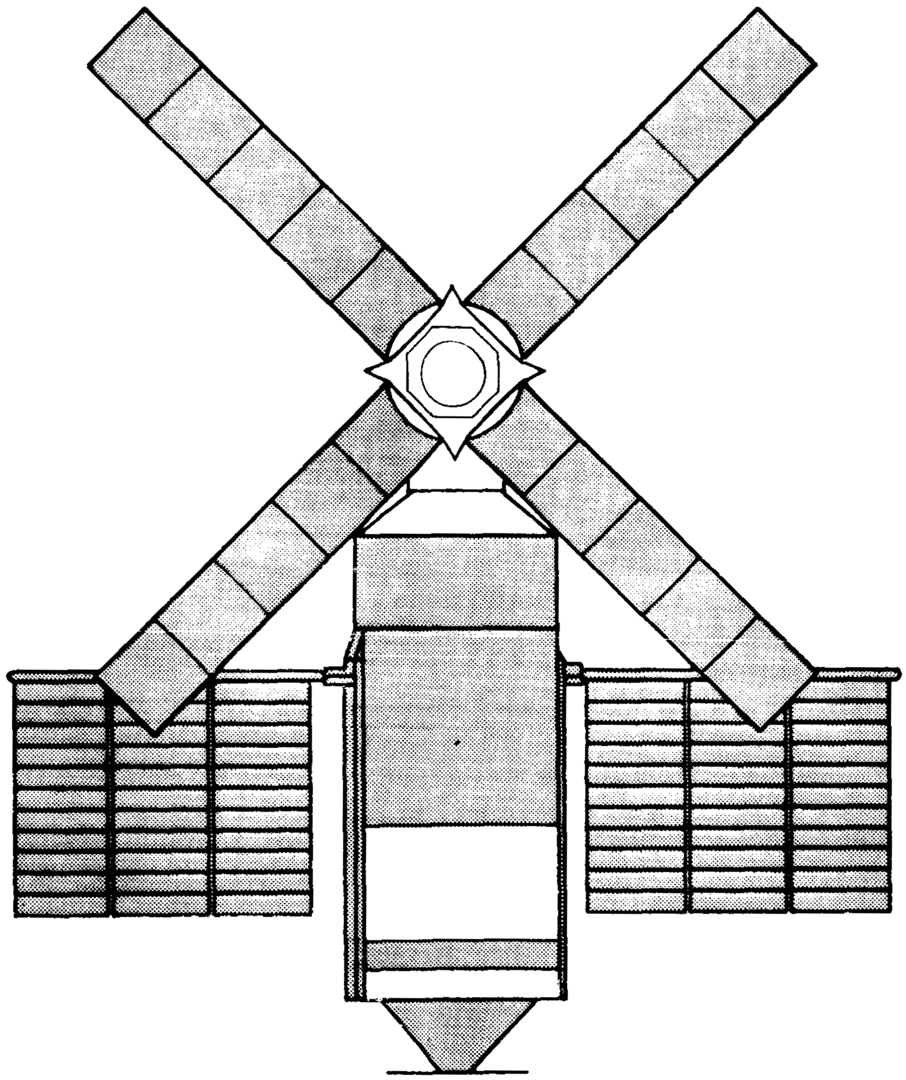


NOTES: 1) $\rho_c \sim$ DESIGNATES REFLECTIVITY

2) $\rho_c \simeq 0.1$ PROVIDES NEAR ZERO (BLACK) REFLECTION

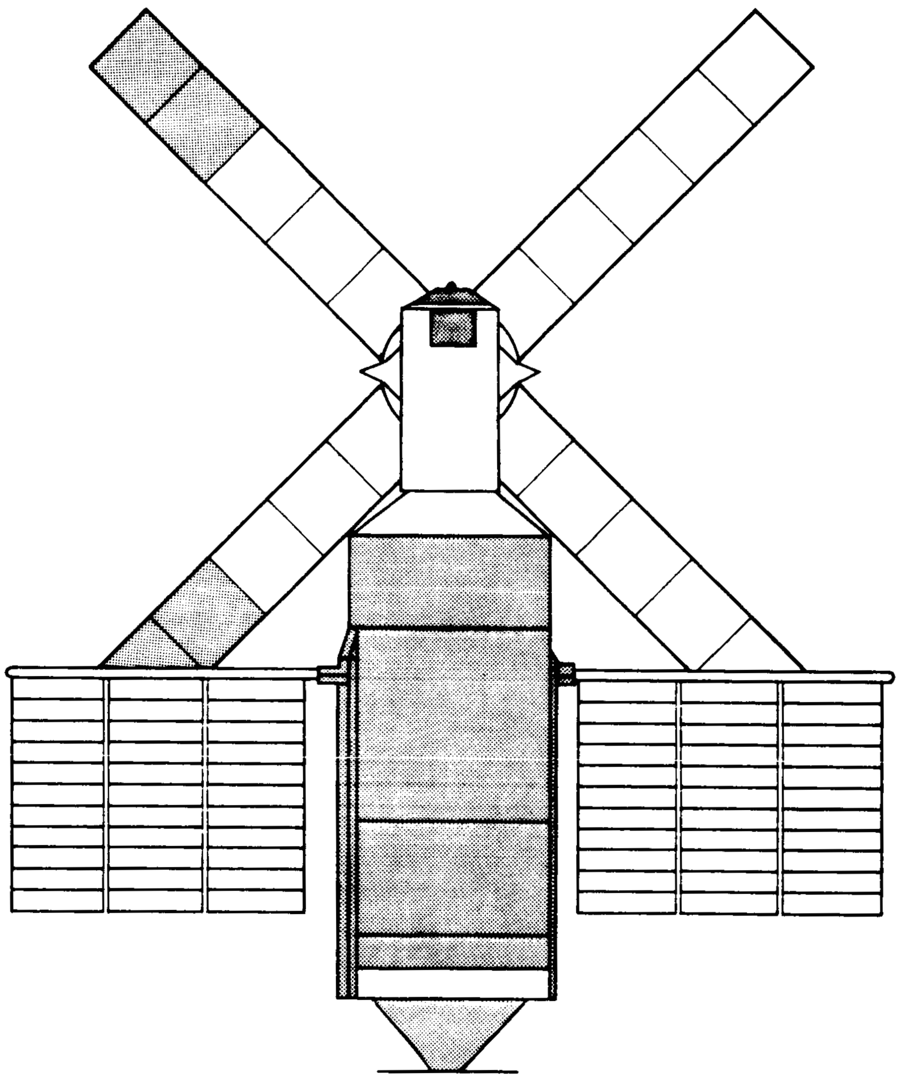
3) $\rho_c \simeq 0.7$ PROVIDES WHITE DIFFUSE REFLECTION

FIGURE 2 - PAINT PATTERN, SWS SIDE VIEW



(THIS VIEW FACES SUN DURING SOLAR INERTIAL)

FIGURE 3 - PAINT PATTERN, SWS FRONT VIEW



(THIS VIEW FACES AWAY FROM SUN DURING SOLAR INERTIAL)

FIGURE 4 - PAINT PATTERN, SWS BACK VIEW

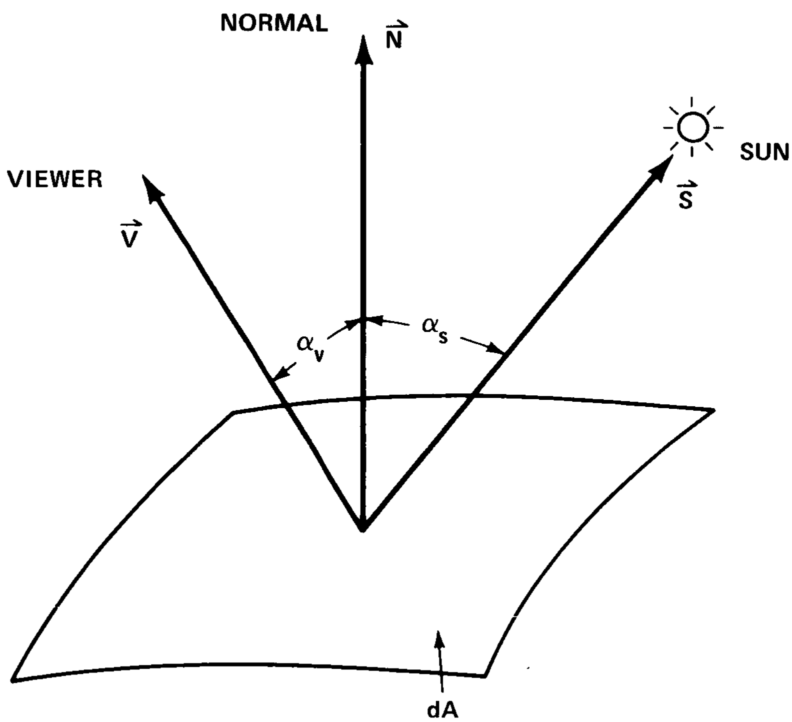


FIGURE 5 - LAMBERT DIFFUSE REFLECTION FROM A DIFFERENTIAL AREA

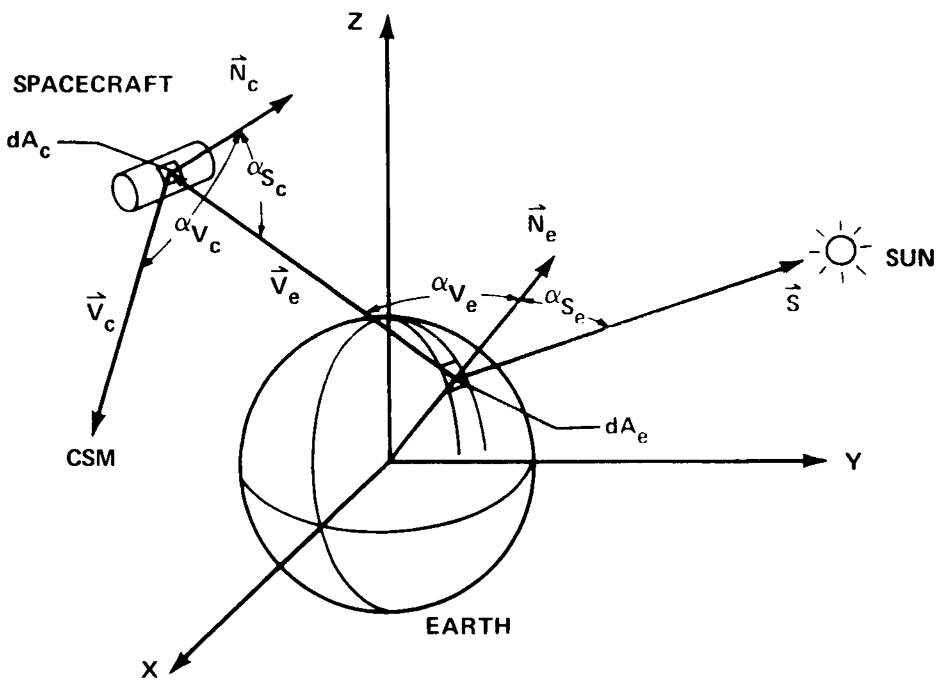


FIGURE 6 - DIFFERENTIAL LUMINOUS INTENSITY FROM THE SWS IN THE DIRECTION OF THE CSM DUE TO EARTH REFLECTED SOLAR LIGHT

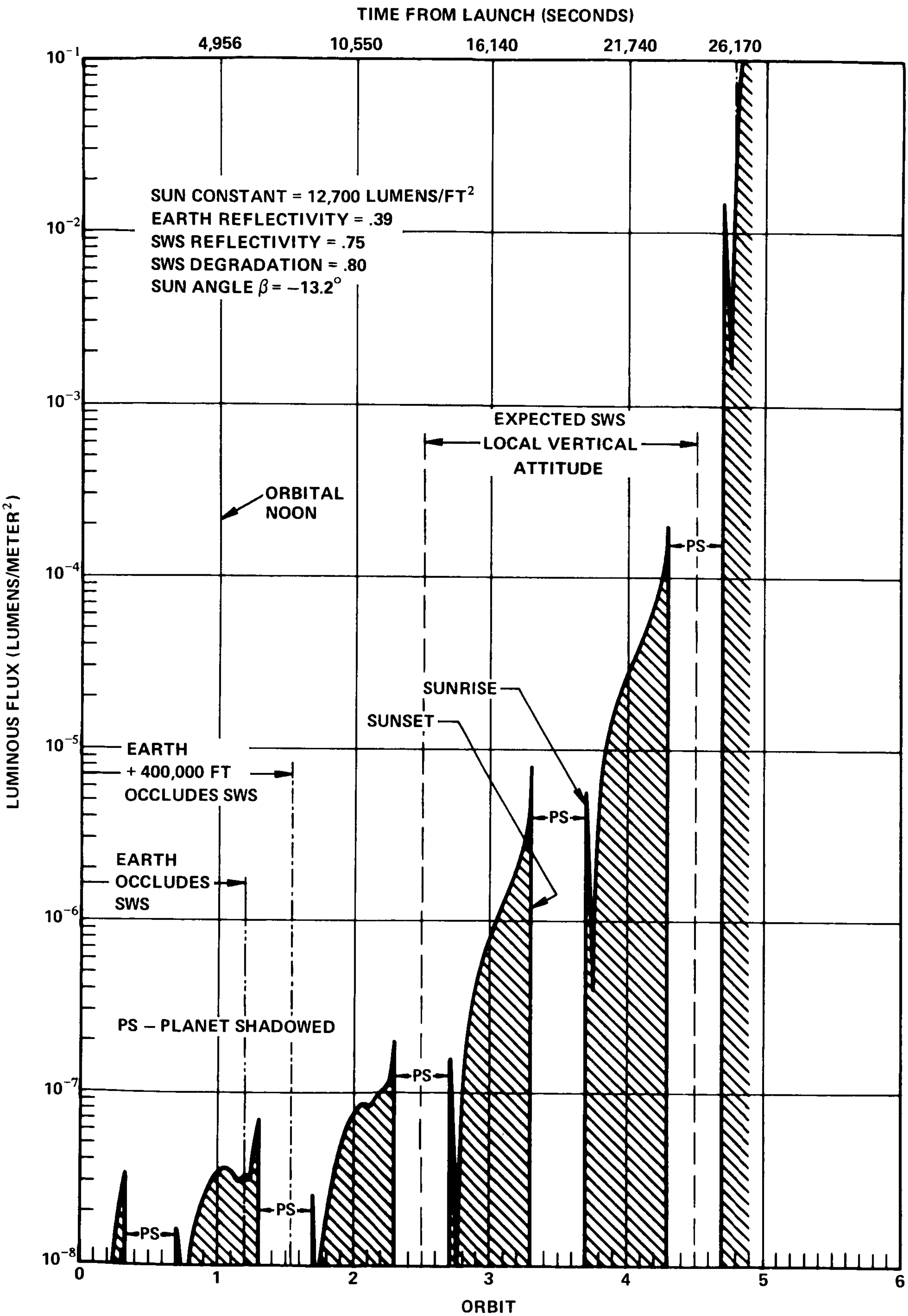


FIGURE 7 - SWS REFLECTED LUMINOUS FLUX AT CSM DURING RENDEZVOUS – SWS IN LOCAL VERTICAL ATTITUDE

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